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Design optimization of energy efficient residential buildings in Tunisia

Pyeongchan Ihm [a], Moncef Krarti [b,*]

[a] Department of Architectural Engineering, Dong-A University, South Korea
[b] Civil, Environmental, and Architectural Engineering Department, University of Colorado, CO 80208, United States

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ABSTRACT

A sequential search technique is applied to optimize the design of residential buildings in Tunisia in order to minimize their life cycle energy costs while increasing their energy efficiency. In the analysis, design features of air-conditioned single-family homes (i.e., villas) are considered including orientation, window location and size, glazing type, wall and roof insulation levels, lighting fixtures, appliances, and efficiencies of heating and cooling systems. First, the results of the sequential search technique are compared against those obtained by a more time consuming brute-force optimization approach. Then, the optimal design features for villas are determined for selected locations in Tunisia. The optimization results indicate that adding roof insulation, reducing air infiltration, installation energy efficient appliances, lighting fixtures, and heating and cooling equipment are required energy efficiency measures to design high energy performance homes throughout climatic zones in Tunisia. In particular, it is found that implementing these measures can cost-effectively reduce the annual energy use by 50% compared to the current design practices of homes in Tunisia.

1. Introduction

In order to reduce building energy consumption and increase its energy performance, an integrated design approach is recommended to evaluate a wide range of energy efficiency measures or EEMs. This approach is especially required when designing high performance buildings targeting net-zero energy use and carbon-neutral level [1–7]. The interactive effects of various EEMs can be difficult to assess without the use of detailed simulation tools. Typically, building designers perform a series of parametric analysis to evaluate the impact and cost-effectiveness of individual energy efficiency measures. This type of parametric analysis often neglects the interactive effects between various measures on building energy use and thus may not select the most cost-effective building design features that provide the highest energy efficiency level at an optimal cost. More comprehensive set of parametric analyses that involves the simultaneous evaluation of several energy efficiency measures require significant computer efforts and are often not considered in the design phase of residential buildings. To overcome the deficiencies the parametric analysis approach, optimization-based design methodology has been proposed to identify and select design and operating measures in order to minimize energy costs for residential buildings. Specifically, optimization-based approaches have been utilized to select building shapes as well as building envelope design features using a wide range of optimization techniques [8–11]. In particular, Tuhus-Dubrow and Krarti developed a simulation environment using genetic algorithm optimization technique to select the best combinations of several building envelope features in order to optimize energy consumption and life cycle costs [12]. Bichiou and Krarti compared the performance of three optimization techniques to select HVAC system design features and its operation settings [13]. The optimization techniques include genetic algorithm, particle swarm optimization, and sequential search methodology.

In Tunisia, the number of residential buildings has increased significantly during the last few decades. Indeed, it is estimated that housing units (including single-family homes and apartment residential units) has grown from 1 million in 1975 to more than 2.7 million in 2007 [14]. Due to this increase in housing units, the energy consumption associated with residential building sector has increased continuously over the last three decades in Tunisia. Moreover, due to living standard improvements, the energy use per housing unit has increased from 0.3 ton of equivalent petroleum or TEP/unit in 1990 to 0.41 TEP/unit in 2006. This increase in energy consumption per housing unit has resulted from a change in the distribution of energy end uses, especially those associated with space air conditioning. Indeed, the energy use for heating and cooling equipment has jumped from 20% in 1989 to 26% in 2004 in the Tunisian residential building sector [15]. Only few studies were carried out to investigate the impact of design and operating

* Corresponding author. Tel.: +1 303 492 3389/7371.
E-mail addresses: krarti@colorado.edu, moncef.krarti@colorado.edu (M. Krarti).

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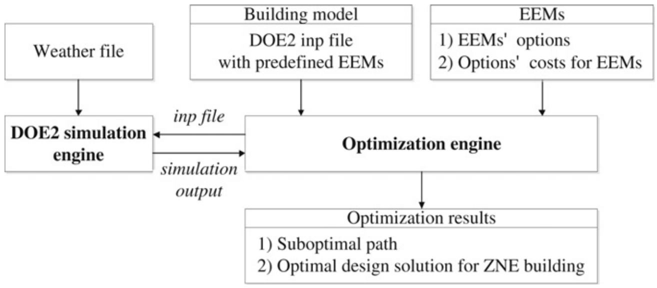

Fig. 1. Flowchart for the simulation environment used for the optimization analysis.

conditions on energy efficiency of Tunisian residential buildings. Some of the studies focused on the impact of only few design features [16–19] or use simplified analysis methodologies [20,21]. However, very limited investigations have focused on the cost-effectiveness of a wide-range of energy efficiency measures on residential buildings in Tunisia.

The objective of the analysis presented in this paper is to investigate cost-effective design and operating features that minimize the life-cycle costs while maximizing energy efficiency and thermal comfort for single-family homes in Tunisia. First, general features and energy efficiency measures associated with a Tunisian prototypical single-family house are described. Moreover, a sequential search optimization technique used in the analysis is briefly presented. Then, the results obtained from the sequential search optimization analysis are validated against a brute-force parametric analysis approach. Finally, a set of recommendations is provided to improve the design of single-family homes in various Tunisian climatic zones.

2. Analysis methodology

To perform the analysis, a simulation environment that utilizes a detailed building simulation as well as a sequential search optimization technique to determine the best path to minimize life cycle costs while reducing the energy use of a prototypical single-family home in Tunisia. Fig. 1 illustrates a flowchart for the simulation environment as well as its components.

The various components of the simulation environment are described in following the sections including the basic characteristics of a prototypical Tunisian home, the energy efficiency measures, and the climatic zones considered in the analysis.

2.1. Building description

Table 1 summarizes the basic characteristics of a prototypical single-family home in Tunisia. These characteristics are developed based on the results of a survey conducted as part of the efforts to develop an energy efficiency code for residential buildings in Tunisia [15]. Fig. 2 provides a 3-D rendering of the prototypical home (often, referred to in Tunisia as a villa). The home has 3 bedrooms and 2 living rooms and is air conditioned with a split system and a hot water baseboard system. A natural gas boiler is utilized to generate the hot water supplied to the baseboards. The cooling setpoint is kept at 24 °C during summertime, and heating setpoint at 22 °C during wintertime.

Table 1
Characteristics of a prototypical single-family home in Tunisia.

Number of floors	2 stories
Floor area	221 m^2 (2379 ft^2)
Floor-to-floor height	3 m (9.8 ft)
Exterior wall area	381 m^2 (4101 ft^2)
Window area	95.2 m^2 (1025 ft^2)
Window-to-wall ratio	25% of all directions
Number of bedrooms	3
Number of bathrooms	2
Cooling System	Split system residential air conditioner (electricity)
Heating System	Baseboard (natural gas)

2.2. Energy efficiency measures

In this analysis, the most common design and operating energy efficiency measures available in Tunisia for residential buildings are evaluated. Table 2 lists eleven EEMs considered for the optimization analysis. These measures and associated options include building envelope, lighting, appliances, temperature settings, and HVAC systems. A brief discussion of the options associated with each EEM is provided below:

- Orientation defined by the azimuth angle between the true south and the front of the house. Seven options for the orientation are considered varying from 0° (baseline) to 270°.
- Exterior wall and roof insulation defined by the thickness of polystyrene insulation. Four options are considered with a no insulation (RSI = 0) to 6-cm insulation (RSI-3.0).
- Window size defined by the window-to-wall ratio (WWR). Four options are evaluated ranging from small windows (WWR = 10%) to large windows (WWR = 40%).
- Glazing type characterized by the number of panes and the coating type applied to the glazing surfaces. Six glazing types are considered in the analysis.
- Lighting type defined by the lighting power density. Four lighting options are considered including (i) all fixtures are incandescent lamps (baseline with 7.3 W/m^2), (ii) 1/3 of the fixtures are compact fluorescent lamps (CFLs) while the other remain incandescent lamps (i.e., 30% reduction in baseline lighting power density), (iii) 2/3 of the fixtures are CFLs while the other remain incandescent lamps (i.e., 50% reduction in baseline lighting power density), and (iv) all the fixtures are CFLs (i.e., 70% reduction in baseline lighting power density).

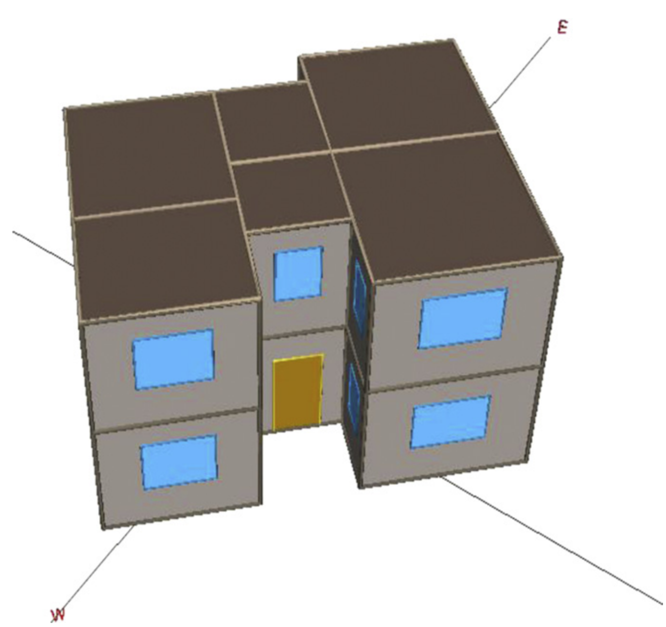

Fig. 2. Isometric of a prototypical villa in Tunisia.

Table 2
Cost data for villa design measures and associated options used for the optimization analysis.

EEM	Specification	Options	Cost
Azimuth	Orientation of the building relatively to the north	**0**, 45, 90, 135, 180, 225, 270	**0 TND for all options**
Exterior wall Construction	Wall insulation (Outdoor installation)	**No insulation**	**54.9 TND/m^2**
		RSI-1.0 (R-5.7) Polystyrene (2 cm thickness)	59.2 TND/m^2
		RSI-2.0 (R-11.4) Polystyrene (4 cm thickness)	62.0 TND/m^2
		RSI-3.0 (R-17.0) Polystyrene (6 cm thickness)	64.6 TND/m^2
Roof Construction	Roof insulation	**No insulation**	**85.0 TND/m^2**
		RSI-1.0 (R-5.7) Polystyrene (2 cm thickness)	90.0 TND/m^2
		RSI-2.0 (R-11.4) Polystyrene (4 cm thickness)	94.0 TND/m^2
		RSI-3.0 (R-17.0) Polystyrene (6 cm thickness)	116.3 TND/m^2
WWR	Window to Wall Ratio	10%, 20%, **25%**, 30%, 40%	**0 TND for all options**
Window Type	Glazing type for window	**Single Clear (6 mm, U: 6.172 W/m^2·°c),**	**25.0 TND/m^2**
		Single Bronze (6 mm, U: 6.172 W/m^2·°c),	32.3 TND/m^2
		Single Low-e (6 mm, U: 4.270 W/m^2·°c)	60.3 TND/m^2
		Double Clear (6/6/6 mm, U: 3.163 W/m^2·°c),	54.9 TND/m^2
		Double Bronze (6/6/6 mm, U: 3.160 W/m^2·°c),	64.6 TND/m^2
		Double Low-e (6/12/6 mm, U: 1.658 W/m^2·°c)	85.0 TND/m^2
Lighting Density	Building Lighting Level	**Typical (7.3 W/m^2)**	**0.4 TND/m^2**
		30% Reduction	0.6 TND/m^2
		50% Reduction	1.0 TND/m^2
		70% Reduction	1.3 TND/m^2
Infiltration	Air Infiltration Level	**Typical (0.7 L/s/m^2)**	**0.0 TND/m^2**
		25% Reduction	0.6 TND/m^2
		50% Reduction	1.2 TND/m^2
		75% Reduction	1.7 TND/m^2
Cooling Set point	Temperature Set-Point for cooling	**24°C (75.2°F)**, 25 °C (77 °F), 26 °C (78.8 °F)	**0 TND for all options**
Refrigerator	Electricity Consumption Level	**Typical (180W: 800 kWh/year)**	**300 TND/Unit**
		Class 3: 30% Reduction	450 TND/Unit
		Class 2: 45% Reduction	600 TND/Unit
		Class 1: 65% Reduction	700 TND/Unit
Boiler	Efficiency [%]	**80**	**700 TND/Unit**
		85	800 TND/Unit
		90	950 TND/Unit
		95	1100 TND/Unit
Air-Conditioner	Coefficient of Performance (COP)	**2.6**	**500 TND/Unit**
		3.0	650 TND/Unit
		3.3	800 TND/Unit
		3.5	1000 TND/Unit

Note: Insulation R-value is expressed in RSI (m^2.°C/W) and R (hr.ft^2.°F/Btu).

- Air leakage level defined by the air infiltration rate. Four levels are considered: leaky (baseline with an infiltration rate of 0.7 L/s/m^2), moderate leakage level with 25% reduction in baseline infiltration rate, good leakage level with 50% reduction in baseline infiltration rate, and tight level with 75% reduction in baseline infiltration rate.
- Cooling temperature setting defined by the maximum acceptable indoor temperature needed to maintain thermal comfort. Three temperature settings are evaluated 24 °C, 25 °C, and 26 °C.
- Refrigerator energy efficiency level defined by its class label [15]. Four options are considered: baseline with an annual use consumption of 800 kWh/year, refrigerator of class 3 with 30% reduction in baseline annual energy consumption, refrigerator of class 2 with 45% reduction in baseline annual energy consumption, and refrigerator of class 1 with 65% reduction in baseline annual energy consumption.
- Boiler type defined by its energy efficiency level. Four energy efficiency levels are considered: 80% (baseline with low-efficiency), 85% (standard efficiency), and 90% (high efficiency), and 95% (premium efficiency consisting of a condensing boiler).
- Cooling system type defined by its coefficient of performance or COP level. Four COP levels are considered: COP = 2.6 (baseline with low-efficiency), COP = 3.0 (standard efficiency), and COP = 3.3 (high efficiency), and COP = 3.5 (premium efficiency).

The options highlighted in bold of each energy efficiency measure listed in Table 2 are the baseline design options commonly used to construct residential buildings in Tunisia. The characteristics of the baseline design are defined based on the results of a comprehensive survey for several homes in Tunisia [15]. For instance, the window to wall ratio (WWR) of the baseline building model is 25%. In addition, Table 2 summarizes the cost of implementing each EEM option. There are about 10.1 million possible combinations of building design options that can be considered for a full parametric analysis (i.e., brute force approach). This large number of combinations requires significant computing time as will be discussed in the validation section of the optimization method. The simulation environment utilizes DOE-2 as the whole-building energy simulation engine to identify the detailed building energy performance [22].

2.3. Climatic zones

In Tunisia, three distinct climatic zones have been recommended by ANME as illustrated in Fig. 3 [23]:

- Mediterranean region of ZT1 is the coastal zone extending from the Bizerte to the Medenine Governorates.
- Climate zone ZT2 covers the western plateaux surrounding northern Tunisia, from the Jendouba to the Gafsa Governorates.
- Climate zone ZT3 covers the Governorates of Tozeur, Kebili and Tataouine in southern Tunisia.

In the analysis considered in this study, four sites have been considered, two sites in ZT1 (Tunis and Mednine), and one site for ZT2 (Gafsa), and one site for ZT3 (Nefta) as shown in Fig. 3.

Fig. 3. Three climate zones and the selected cities in Tunisia.

2.4. Economic analysis

The simulation environment can consider a wide range of cost functions and sets of constraints to perform the optimization analysis. In this paper, the cost function is selected as the life cycle cost or LCC as defined by Eq. (1) [24].

$$LCC = IC + USPW(N, r_d)^*EC \tag{1}$$

where,

- IC: is the initial cost for implementing all the design and operating features for both building envelope and HVAC system. Table 2 provides the cost data for various design and operating options.
- EC: is the annual energy cost to maintain indoor comfort within the residential building for the selected design and operating features.
- USPW: is the uniform series present worth factor which depends on the annual discount rate, r_d and life time N.

$$USPW(N, r_d) = \left[1-(1+r_d)^{-N}\right]\Big/r_d \tag{2}$$

Throughout the optimization analysis presented in the paper, the life time is set to be $N = 30$ years and the annual discount rate to $r_d = 5\%$. These values are typically based on the lifespan of typical homes as well as the economic parameters in Tunisia [15]. The utility rate in Tunisia is considered as electricity cost of 0.138 TND/kWh and natural gas of 0.238 TND/m^3 in this analysis [19].

2.5. Interactive effect analysis

Using the simulation environment, the interactive effect between various EEMs can be assessed. For instance, implementing energy efficient lighting affects both heating and cooling loads and therefore can affect the impact of other EEMs such as adding wall and roof thermal insulation or installing premium boilers or air conditioners. To measure the level of interaction between EEMs when they are combined in a design set, a parameter f_{int} is defined by Eq. (3):

$$f_{int} = 1 - \Delta E_{all}/\Delta E_{max} \tag{3}$$

Where:

- ΔE_{all} are the source energy use savings that can be achieved when all the measures for a given set are implemented
- ΔE_{max} are the source energy use savings obtained by simply adding the maximum savings found from each EEM of the set.

When there is no interaction between EEMs, the value of f_{int} approaches zero (i.e., $f_{int} = 0$).

3. Optimization approach

3.1. Overview of the optimization technique

The optimization method used in the simulation environment identifies the optimal building design options from multiple possible alternatives using a sequential search methodology. This optimization approach is first applied to design zero-net energy (ZNE) buildings [25,26]. It has been also utilized for other applications including optimized selection of building shape, wall and roof constructions, and HVAC systems [12,13]. Fig. 4 illustrates the sequential search optimization approach to find a path that reaches the optimal package of EEMs that provides the lowest life cycle cost as defined by Eq. (1). The optimization method finds also the suboptimal path to design ZNE building. First, all the EEMs are individually considered for an initial building design with a specific life cycle cost. Then, the most cost-effective EEM option is chosen based on the steepest slope consisting of the LCC to energy savings ratio. The selected EEM optimal option is then removed from the parameter search space for future evaluation, and then the remaining EEMs are simulated to find the next optimal option. This process is repeated until the optimal solution is reached. The advantage of the sequential search optimization methodology is to find multiple solutions which include the optimal and near-optimal options as shown in Fig. 4 to select a best combination of building design features. That is, the approach finds the intermediate optimal solutions for the minimum cost designs at various levels of energy savings. Indeed, the approach can provide in addition to the optimal solution, a set of options that achieve any set of desired energy use savings that reduces the life cycle cost before the optimal solution is reached. Thus, an optimal path to achieve various levels of energy use savings at the lowest life cycle costs can be obtained using the sequential search technique [27–29].

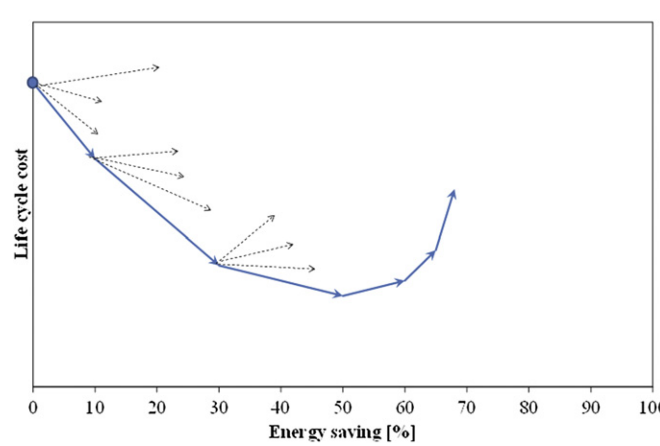

Fig. 4. Basic sequential search optimization approach to find optimal solution.

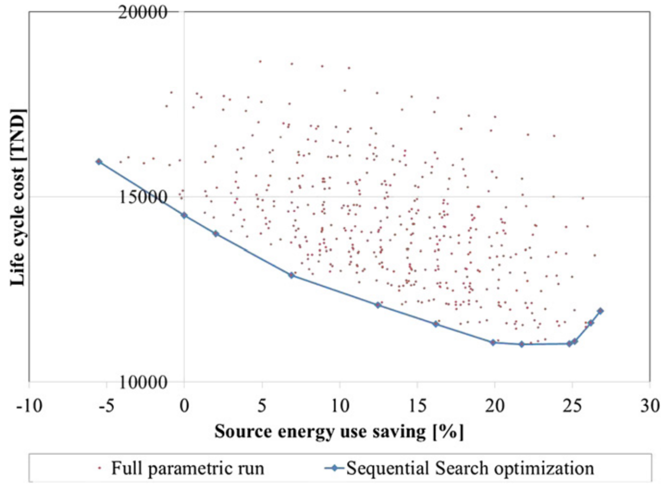

Fig. 5. Comparison of optimal results obtained by the brute force analysis and the sequential search optimization for 4-EEM package when the villa is located in Tunis.

The developed simulation environment used in the optimization analysis is designed to easily accept and identify optimal packages of EEMs to reduce life cycle costs of constructing and operating residential buildings in Tunisia. It should be noted that the simulation environment can be extended and applied to any other type of buildings.

3.2. Validation of optimization results

In this section, the results obtained from the sequential search optimization are compared with a brute-force search approach that utilizes the full combination options of energy efficiency measures to find the optimum design package for a prototypical single-family home in Tunisia.

As noted earlier, the computational efforts to find optimal design values for eleven EEMs (about 11.1 million possible combination of building design options) are significant and may take several months to complete using the current state-of-the art computing processors. Instead, three analysis cases are considered with different number of EEMs described in Table 2 to validate the results of the sequential search optimization approach. The three

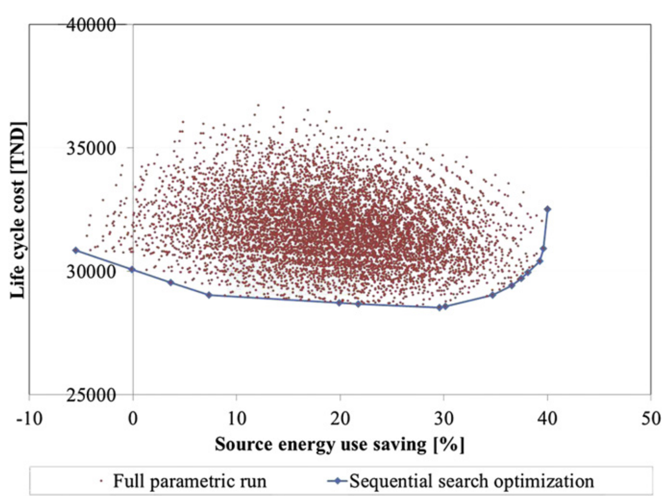

Fig. 6. Comparison of optimal results obtained by the brute force analysis approach and the sequential search optimization for the 6-EEM package when the villa is located in Tunis.

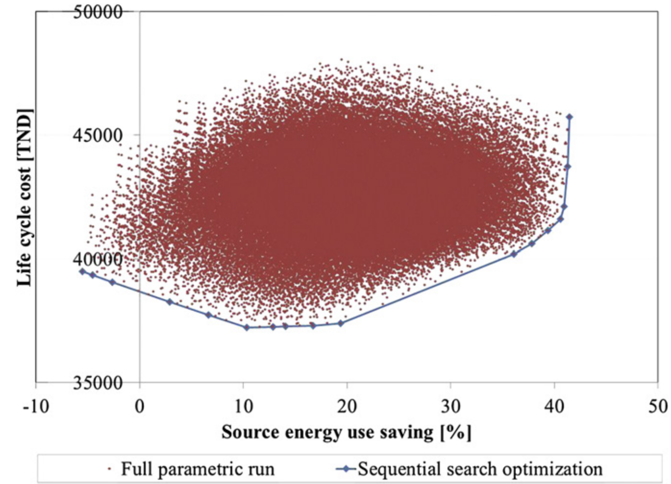

Fig. 7. Comparison of optimal results obtained by the brute force analysis approach and the sequential search optimization for the 8-EEM package when the villa is located in Tunis.

considered analysis cases consist of different combinations of design options:

1) 4-EEM package: WWR, glazing type, lighting level, infiltration rate,
2) 6-EEM package: exterior wall insulation, roof insulation, WWR, glazing type, lighting level, Infiltration rate, and
3) 8 EEM package: indoor and exterior wall insulation, roof insulation, WWR, glazing type, lighting level, infiltration rate, cooling set point.

Figs. 5–7 compare the sequential search optimization results obtained for the three EEM-packages when the house is located in Tunis against those obtained with the full brute force approach (i.e., all combinations of options are considered). The results in Fig. 5 through 7 are presented in terms of pareto diagrams showing life cycle cost as a function of percent savings of total building source energy use. Table 3 summarizes the comparative results for the brute-force analysis and the sequential search optimization approach. As indicated in Fig. 5 through 7 as well as Table 3, the sequential search optimization technique finds the same optimum solutions found through the brute force technique for the three analysis cases. The computational time of the sequential search technique (4.6 min) is significantly lower by up to 99.7% to that of the brute force analysis approach (28.9 h) for the 8-EEM package analysis case using a 2.8-HGZ processor.

4. Optimization results

4.1. Effectiveness of design measures

Table 4 and Fig. 8 summarizes the results of source energy savings and life cycle costs compared to those obtained for

Table 3
Summary of comparative results between brute force analysis and sequential search optimization for three analysis cases when the villa is located in Tunis.

Number of EEMs	Number of possible building design options	Computing time for brute-force analysis [min]	Computing time for sequential search [min]	Reduced CPU time [%]
4	480	7.0	2.1	69.9
6	7680	123.5 (2.1 h)	3.1	97.5
8	92,160	1732.8 (28.9 h)	4.6	99.7

Table 4
Summary of impact of individual design measures for a villa located in Tunis.

Parameter	Options	Annual Electricity Use (kWh)	Annual Natural Gas Use (MJ)	Annual Source Energy savings (%)	Life cycle Cost (TND)
Base case		5666	14,876	0	32,281
Azimuth (degree)	45	5707	14,771	−0.4	32,357
	90	5666	14,560	**0.4**	32,251
	135	5762	14,454	−0.8	32,443
	180	5725	14,138	0.1	32,335
	225	5774	14,349	−0.8	32,458
	270	5678	14,454	0.4	32,266
Exterior wall insulation	RSI-1.0 (R-5.7) Polystyrene (2 cm thickness)	5611	13,821	2.2	32,850
	RSI-2.0 (R-11.4) Polystyrene (4 cm thickness)	5608	13,399	2.8	33,314
	RSI-3.0 (R-17.0) Polystyrene (6 cm thickness)	5607	13,188	**3.1**	33,763
Roof insulation	RSI-1.0 (R-5.7) Polystyrene (2 cm thickness)	5542	13,716	3.3	32,275
	RSI-2.0 (R-11.4) Polystyrene (4 cm thickness)	5530	13,505	3.7	32,524
	RSI-3.0 (R-17.0) Polystyrene (6 cm thickness)	5551	13,399	**3.6**	34,203
WWR [%]	10	5210	14,665	**6.8**	32,049
	20	5533	14,876	1.9	32,250
	30	5792	14,982	−1.9	32,307
	40	6055	14,982	−5.7	32,362
Glazing type	Single Bronze (6 mm, U: 6.172 W/m^2·°C)	5515	15,615	1.2	32,353
	Single Low-e (6 mm, U: 4.270 W/m^2·°C)	5526	13,927	3.2	33,441
	Double Clear (6/6/6 mm, U: 3.163 W/m^2·°C)	5501	14,138	3.3	33,173
	Double Bronze (6/6/6 mm, U: 3.160 W/m^2·°C)	5358	14,771	4.5	33,356
	Double Low-e (6/12/6 mm, U: 1.658 W/m^2·°C)	5231	14,032	**7.3**	33,913
Lighting level	30% Reduction	5263	14,982	5.6	31,482
	50% Reduction	4992	15,087	9.3	30,969
	70% Reduction	4721	15,193	**13.0**	30,456
Infiltration level	25% Reduction	5609	14,138	1.8	32,222
	50% Reduction	5550	13,188	3.9	32,139
	75% Reduction	5502	12,450	**5.5**	32,099
Cooling Set point	25 °C (77 °F)	5608	14,876	0.8	32,159
	26 °C (78.8 °F)	5483	14,876	2.6	31,896
Refrigerator energy level	Class 3: 30% Reduction	5191	14,982	6.6	31,391
	Class 2: 45% Reduction	4954	14,982	10.0	31,042
	Class 1: 65% Reduction	4638	14,982	**14.5**	30,526
Boiler efficiency [%]	85	5666	14,243	0.8	32,321
	90	5666	13,610	1.7	32,411
	95	5666	12,977	**2.5**	32,501
Air-Conditioner COP	3	5493	14,876	2.5	32,067
	3.3	5390	14,876	3.9	32,050
	3.5	5332	14,876	**4.7**	32,078

1 TND = 0.68 US$.

a baseline single-family house located in Tunis for each design option. The results of Table 4 indicate the effectiveness of each design measure when implemented individually on both energy use and life cycle costing. As expected, a home built with energy-efficient measures such as adding insulation, improving glazing type, and lowering lighting level, save up to 14.5% of total annual energy use when compared to than the baseline house. Based on a survey of energy end uses, it is found that refrigerators and lighting fixtures contribute respectively, 41% and 18% of the total electricity used in a typical home in Tunisia [30]. It is therefore reasonable that the use of energy efficient refrigerators and lighting fixtures have the most impact in reducing source energy use by up to 14.5% and 13%, respectively. The use of double pane low-e glazing instead of single pane clear glazing for all windows saves 7.3% in total villa electricity consumption. For Tunis, small windows (with WWR = 10%) can reduce energy use by 5.7% compared to larger windows (with WWR = 40%) due to lower solar gains. However, changing the orientation of the villa does not seem to have any significant impact on the energy use. Indeed, the total energy use of the villa changes by only 0.8% for all the orientations considered in the analysis. As indicated in Table 4, when adding all savings from the individual EEMs, maximum energy savings of 63.9% is reached. However, this sum of energy savings is not realistic and provides only indication of the potential maximum energy savings since this sum does not take into account the interactive effects between various EEMs. The level of interaction between various EEMs is explored in the following section.

4.2. Optimal combinations of design measures

In this section, the developed optimization simulation environment is used to investigate the interactions between

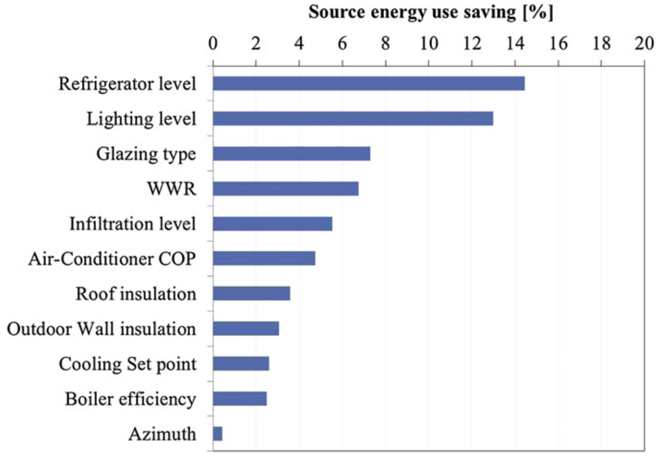

Fig. 8. Maximum source energy use savings for each design measure applied to a villa located in Tunis.

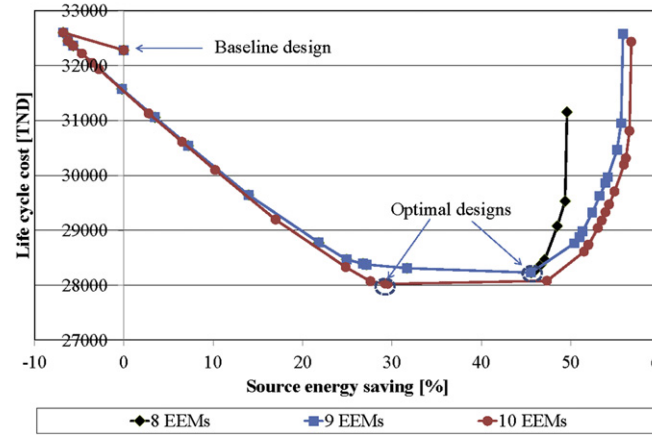

Fig. 9. Comparison of sequential search optimization results for sets of 8, 9 and 10 EEMs.

incremental sets of EEMs listed in Table 4. First, a 2-EEM set is defined to include optimal values of WWR (i.e., 10%) and orientation (i.e., azimuth = 90°). These measures, once defined, are difficult to change due to site and owner specifications. Then, additional EEMs using their optimal options are added incrementally based on their impact ranking listed in Table 4. Therefore, design sets of 2 through 11 EEMs are defined as indicated in Table 5. The energy use as economical performance for all the 9 incremental design sets are summarized in Table 5.

As indicated in Table 5, source energy use savings of the optimal design case relative to the baseline design of the villa can be increased from 6.8% for a set of 2 EEMs -consisting of azimuth and window-to-wall-ratio- to 45.6% for the set that includes 8 EEMs. However, optimal design configurations obtained for sets of 9, 10, and 11 EEMs (obtained by respectively, adding exterior wall insulation, changing cooling set-point, and improving boiler efficiency) do not provide any additional source energy use savings. In fact, there is a reduction of source energy use savings for design sets made up of 10 and 11 EEMs as shown in Table 5. In order to gain more insights on the change of behavior for set of 10 EEMs compared to the sets of 8 and 9 EEMs, optimal paths for the three sets obtained from the sequential search technique are illustrated in Fig. 9. Table 6 provides specific optimal design options selected for the three design sets. It is clear that the addition of exterior wall insulation to the 8-EEM set to form the 9-EEM set, does not result in any significant change in life cycle costs and source energy savings (45.6%) for the optimal design configuration. However, the maximum potential source energy use savings for 8-EEM and 9-EEM sets are significantly different with 49.6% (for the 8-EEM set) and 58.8% (for the 9-EEM set). These results indicate that the addition of insulation in the outer layer of the exterior walls is not a cost-effective measure and thus is not selected as part of the optimal design configuration even though it is an available energy efficiency option for the 9-EEM set. Moreover, the results presented in Table 5 and Fig. 9 indicate that the optimal design configuration for the 10-EEM set (with the possibility to change cooling set-point trough the installation of programmable thermostat) moves the optimal design configuration back to lower source energy use savings of 25% but with slightly lower life cycle cost. As shown in Table 6, when 10-EEM set is used, the cooling set point is increased to 26 °C from 24 °C and a more efficient air conditioner is used (COP is increased from 3.0 to 3.3) compared to the design cases selected for 8-EEM and 9-EEM sets. Moreover, the optimal design for the 10-EEM set uses larger windows (i.e., WWR = 40%) instead of small windows (WWR = 10%) for 8-EEM and 9-EEM sets while maintaining the same glazing type (single-clear). This selection reduces the initial cost of the villa (since the opaque walls cost more to install than windows) and allow reduction in heating loads. This reduction in initial costs allow the optimization to select less energy efficient design options for the 10-EEM set compared to those selected for the 8-EEM or 9-EEM sets (such as no roof insulation and no reduction in air infiltration).

The optimization results for all the sets of EEMs are summarized in Figs. 10 and 11 when the villa is located in Tunis. As illustrated in

Table 5
Summary of the optimization results associated with the incremental sets of design measures for a villa located in Tunis (O: selected design option).

	Number of EEMs										Initial Implementation Cost [TND]	Annual Energy Cost [TND]	Life Cycle Cost [TND]	Energy Savings [%]
	2	3	4	5	6	7	8	9	10	11				
Reference building											18,935	13,346	32,281	0.0
Azimuth	O	O	O	O	O	O	O	O	O	O				
WWR	O	O	O	O	O	O	O	O	O	O	19,683	12,366	32,049	6.8
Refrigerator energy level		O	O	O	O	O	O	O	O	O	20,083	10,206	30,289	21.2
Lighting level			O	O	O	O	O	O	O	O	20,218	8238	28,456	34.4
Glazing type				O	O	O	O	O	O	O	20,218	8238	28,456	34.4
Infiltration level					O	O	O	O	O	O	20,350	8058	28,408	36.3
Air-Conditioner COP						O	O	O	O	O	20,264	8033	28,296	37.6
Roof insulation							O	O	O	O	21,128	7103	28,231	45.6
Exterior wall insulation								O	O	O	21,128	7103	28,231	45.6
Cooling Setpoint									O	O	19,072	8959	28,031	29.2
Boiler efficiency										O	19,072	8952	28,024	29.5

Table 6
Summary of the optimization results for sets of 8, 9 and 10 design measures for a villa located in Tunis.

	8 measures	9 measures	10 measures
Azimuth	270	270	0
WWR	10	10	40
Refrigerator energy level [%]	65	65	65
Lighting level [%]	70	70	70
Glazing type	Single Clear	Single Clear	Single Clear
Infiltration level [%]	75	75	0
Air-Conditioner COP	3	3	3.3
Roof insulation	polystyrene 2 cm	polystyrene 2 cm	No insulation
Exterior wall insulation	No insulation	No insulation	No insulation
Cooling Setpoint [°C]	24	24	26
Boiler efficiency [%]	80	80	80
Initial cost [TND]	21,128	21,128	19,072
Utility cost [TND]	7103	7103	8959
Life cycle cost [TND]	28,231	28,231	28,031
Energy savings [%]	45.6	45.6	29.2

Fig. 10, the source energy use savings increases continuously to 45.6% when the number of EEMs in a set increases from 2 to 9. However, the energy savings are reduced by about 16% when 10 or 11 EEMs are considered, that is, when the two EEMs consisting of cooling set-point change and boiler efficiency are considered. As expected, the life cycle costs continue to decrease as the number of EEMs increases. In particular, the decrease in life-cycle cost from 9-EEM to 10-EEM sets is attributed to lower initial costs (from 21,128 to 19,072 TND) even though the energy use costs are increased (from 7103 to 8952 TND).

Fig. 11 provides the level of interaction, f_{int}, between EEMs when they are combined in a design set as defined by Eq. (3). In particular, Fig. 11 compares the source energy use savings, ΔE_{all}, that can be achieved when all the measures for a given set are implemented to those savings, ΔE_{max}, obtained by simply adding the maximum savings for all EEMs of the set as listed in Table 4 when the villa is located in Tunis. As indicated in Fig. 11, there is no significant interaction effect when the set of EEMs includes azimuth, WWR, refrigerator, and lighting. However, some level of thermal interaction does exist between EEMs as the number of sets increases from 5 to 11. Fig. 11 shows that the level of interaction is highest for 7-EEM set with $f_{int} = 16\%$ but it decreases by adding roof insulation (8-EEM set) and exterior wall insulation (9-EEM set) when the interaction level, f_{int}, is reduced to just 5%. The addition of

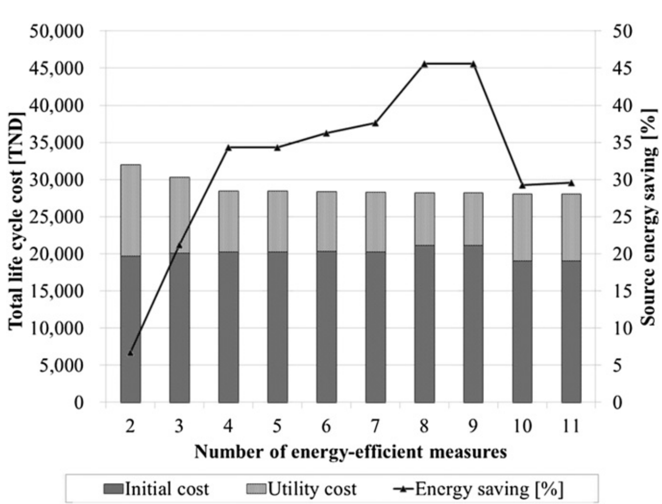

Fig. 10. Optimization results of energy use saving percent and normalized cost against reference building for incremental energy-saving measures in Tunis.

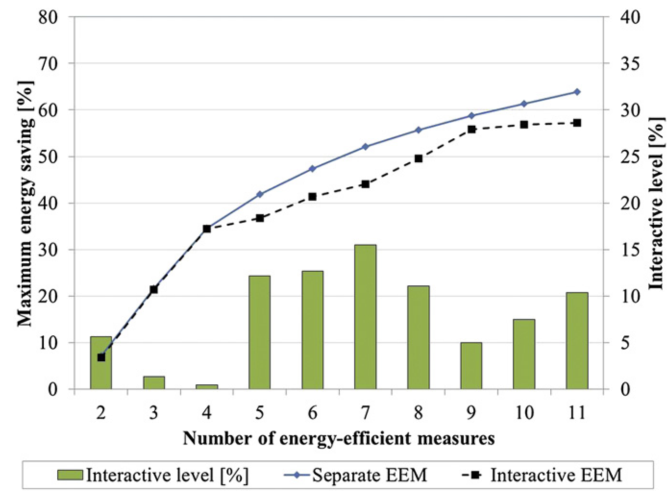

Fig. 11. Maximum energy savings as a function of the number of energy efficiency measures for the residential building in Tunis.

insulation seem to dampen the thermal interaction between various EEMs applied to the villa due most likely to lower heating and cooling loads.

4.3. Impact of climatic conditions

This section investigates the optimum design options for a villa located in four cities selected to represent the three climate zones in Tunisia. Table 7 summarizes the optimization results including villa design features, source energy savings, and life cycle cost for the four sites. The selected optimal building orientation depends on the site. The optimal design options for the exterior wall and roof insulation consist of no or low insulation level. Indeed, Tunisia is located in a rather mild Mediterranean region, thus uninsulated building envelope (especially roof) can be beneficial to let heat escape during cool nights. During the hot days, it is found that the reduction in energy use associated with adding insulation does not compensate for the high implementation costs. In addition, lower boiler efficiency is selected for all the sites. Indeed, all climatic zones in Tunisia are dominated by cooling rather than heating

Table 7
Summary of the residential building design options and costs for minimizing LCC for four Tunisia sites.

	Tunis (ZT1)	Medenine (ZT1)	Gafsa (ZT2)	Nefta (ZT3)
Azimuth [degree]	270	180	90	90
Exterior wall insulation	No insulation	No insulation	No insulation	No insulation
Roof insulation	No insulation	No insulation	polystyrene 2 cm	polystyrene 2 cm
WWR [%]	40	40	10	10
Glazing type	Single clear	Single clear	Single clear	Single Bronze
Lighting level [%]	70	70	70	70
Infiltration level [%]	0	0	75	75
Refrigerator energy level [%]	65	65	65	65
Air-Conditioner COP	3.3	3.5	3	3
Boiler efficiency [%]	80	80	80	80
Cooling Set point [°C]	26	26	26	26
Initial cost [TND]	19,072	19,222	21,128	21,265
Utility cost [TND]	8952	8988	7612	7909
Life cycle cost [TND]	28,024	28,210	28,740	29,174
Energy saving [%]	30	33	48	48

Table 8
Summary of the maximum energy saving potential and associated villa design options for four Tunisia sites.

	Tunis (ZT1)	Medenine (ZT1)	Gafsa (ZT2)	Nefta (ZT3)
Azimuth	180	225	90	270
Exterior wall insulation	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm
Roof insulation	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm
WWR [%]	10	10	10	10
Glazing type	Double Low-e	Double Low-e	Double Low-e	Double Low-e
Lighting level [%]	70	70	70	70
Infiltration level [%]	75	75	75	75
Refrigerator energy level [%]	65	65	65	65
Air-Conditioner COP	3.5	3.5	3.5	3.5
Boiler efficiency [%]	95	95	95	95
Cooling Set point [C]	26	26	26	26
Initial cost [TND]	26,952	26,952	26,952	26,952
Utility cost [TND]	5850	6074	6239	6415
Life cycle cost [TND]	32,803	33,026	33,191	33,367
Energy saving [%]	57	56	59	59

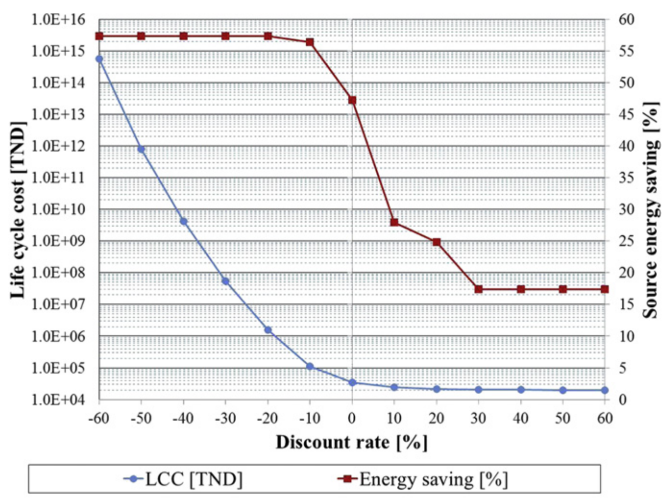

Fig. 12. The impact of annual discount rate on percent source energy use saving and life cycle cost obtained for the optimal villa design for Tunis.

loads. Therefore, there is no need to invest in a high efficiency boiler since it is rarely utilized. As indicated in Table 7, the optimal designs for villas located in ZT1 have less initial costs than those located in ZT2 and ZT3 due to lower number of EEMs. However, the energy costs for villas in ZT1 are higher than those for other zones. Therefore, life cycle costs for all climate zones are similar. Comparing to the baseline design option, optimal design sets result in source energy savings of 30%, 33%, 48%, and 48% when the villa is located respectively in Tunis, Medenine, Gafsa, and Nefta.

Table 8 lists the design options that provide the maximum potential of energy savings for the four sites. As expected, the most energy efficient option when all EEMs are selected results in annual source energy saving of 57% for Tunis, Gafsa, and Nefta, and 56% for Medenine. Therefore, about 27% of source energy saving percent can be achieved relative to the optimal design configuration when the villa is located in Tunis. However, significant increase in initial cost and life cycle costs are incurred in order to achieve the maximum energy use savings as illustrated in Table 8.

4.4. Impact of discount rates

The optimization results of the optimal design selection can be significantly affected by the economic parameters used in the analysis. In particular, Fig. 12 indicates the impact of the annual discount rate on both the life cycle cost and the source energy use percent savings. Table 9 provides the optimal design measures for selected annual discount rate values. As expected, both the life cycle cost and percent source energy use savings decreases for higher annual discount rates. Indeed, energy-efficiency measures become more cost-effective with lower annual discount rates (negative discount rates are associated to high inflation and energy escalation rates). In particular, all the possible measures are selected for the optimal design of the villa located in Tunis when the annual discount rate becomes equal or lower than −20% resulting in source energy use savings of 57.3%. For more typical annual discount rate values around 5%, the optimal design

Table 9
Summary of the optimization results for selected of annual discount rate values for a villa is located in Tunis.

	−60%	−40%	−20%	0%	20%	40%	60%
Azimuth	180	180	0	0	0	270	270
Exterior wall insulation	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm	No insulation	No insulation	No insulation	No insulation
Roof insulation	polystyrene 6 cm	polystyrene 6 cm	polystyrene 6 cm	polystyrene 2 cm	No insulation	No insulation	No insulation
WWR [%]	10	10	10	10	40	40	40
Glazing type	Double Low-e	Double Low-e	Double Low-e	Single Bronze	Single Clear	Single Clear	Single Clear
Lighting level [%]	70	70	70	70	70	70	70
Infiltration level [%]	75	75	75	75	0	0	0
Refrigerator energy level [%]	65	65	65	65	65	30	30
Air-Conditioner COP	3.5	3.5	3.5	3	2.6	2.6	2.6
Boiler efficiency [%]	95	95	95	80	80	80	80
Cooling Set point [C]	26	26	26	26	26	26	26
Initial cost [TND]	26,952	26,952	26,952	21,265	18,722	18,422	18,422
Utility cost [TND]	5.5016E+14	4,303,706,610	1,529,987	13,282	3112	1751	1167
Life cycle cost [TND]	5.5016E+14	4,303,733,562	1,556,939	34,547	21,834	20,173	19,589
Energy saving [%]	57.3	57.3	57.3	47.2	24.8	17.4	17.4

measures can achieve 40% source energy savings. Even when the annual discount rates become high (over 30%), savings of about 20% in source energy use by the villa can be obtained since investments in energy efficient lighting systems and appliances remain cost-effective as indicated by Table 9.

5. Summary and conclusions

A simulation environment is developed based on a sequential search technique, life cycle cost analysis, and detailed building energy modeling in order to optimize the design of energy-efficient single-family homes in Tunisia. In the analysis, a wide range of design and operating measures are considered including orientation, window location and size, glazing type, wall and roof insulation levels, lighting fixtures, appliances, and efficiencies of heating and cooling systems. It is found that source energy use savings up to 59% can be achieved cost-effectively using an optimal design compared to the current construction practices of homes in Tunisia. Moreover, it is found that the specific selection of optimal design features vary depending on the climatic and economic conditions. Typically, adding roof insulation, reducing air infiltration, installation energy efficient appliances, lighting fixtures, and heating and cooling equipment are common energy efficiency measures recommended for optimal homes designs for all climatic zones in Tunisia.

The developed simulation environment is found to be flexible in providing a wide range of desired outcomes. Indeed, the sequential search technique allows the identification of not only the optimal design but also the most cost-effective set of energy efficiency measures that can achieve a desired energy use saving level including the net-zero energy design configuration. The results can be used to help homeowners and architects design high performance residential buildings in Tunisia. It can be easily extended to evaluate other types of buildings.

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